Biodiversity Series

Placement of CO_2 in Subsea Geological Structures

OSPAR Commission
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The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. It has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland and the United Kingdom and approved by the European Community and Spain.

La Convention pour la protection du milieu marin de l'Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d'Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. La Convention a été ratifiée par l'Allemagne, la Belgique, le Danemark, la Finlande, la France, l'Irlande, l'Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni de Grande Bretagne et d'Irlande du Nord, la Suède et la Suisse et approuvée par la Communauté européenne et l'Espagne.

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Summary

This report responds to the request of the OSPAR Commission, on the basis of a proposal from its Biodiversity Committee, to include in the work programme of its Offshore Industry Committee for 2005/2006:

i. a review of the risk characterisation for selection of potential sites in the OSPAR maritime area for the storage of CO_2 , taking account of the different types of site;

ii. a review of appropriate monitoring and surveillance mechanisms for the purposes of detecting leakage of CO_2 from sub-seabed reservoirs and releases of CO2 into the marine environment.

Carbon dioxide (CO_2) capture and storage (CCS) means separation of CO_2 from industrial and energy-related sources, transport to a storage location, and long-term isolation from the atmosphere. CCS is considered by the Intergovernmental Panel on Climate Change (IPCC) as an option in a portfolio of climate change mitigation actions (IPCC 2005). This present OSPAR report assesses available reports and literature on environmental impacts of placement of CO_2 in geological structures under the seabed. It focuses on risk categorisation for the selection of storage sites and techniques for monitoring of CO_2 -storage projects. The report focuses solely on injection and storage in *geological* structures, as opposed to storage in the ocean. The main conclusions are:

a) Geological storage of CO_2 is technically feasible and makes use of established technologies.

b) There is a significant potential for geological storage in structures in the OSPAR maritime area.

c) It is technically feasible to develop geological storage in a safe way provided that storage sites are appropriately selected, managed and monitored. For well selected, designed and managed geological storage sites, a retention time for CO_2 of several thousand years can be obtained. In some cases, the vast bulk of the CO_2 will gradually be immobilized by various trapping mechanisms and, in such cases, could be retained for up to millions of years.

d) Risks and effects of leakage of CO_2 stored in geological structures would have to be evaluated against the risk to the marine environment posed by elevated atmospheric levels of CO_2.

e) Evaluation of the capability of a site to store CO_2 in the long term relates to the protection of the marine environment as well as climate change mitigation. Guidelines, or a framework for the assessment of potential storage sites, would be useful. Relevant factors may include characterisation of the reservoir, the cap rock/trapping mechanisms, geological stability and possible leakage-path routes.

f) Appropriate monitoring/surveillance technology and methodology for the safe storage of CO_2 are available, including seismic and gravimetric techniques, and should be used in a site-specific manner to monitor the CO_2 storage; and detect and enable the remediation of leakage. The techniques are based on decades of experience in the oil and gas industry.

1. Introduction

IPCC has concluded that there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities (IPCC 2001). Increasing CO_2 concentrations in the atmosphere will lead to acidification of the oceans, changes in the global climate and increasing average sea temperatures, sea level rise, reduced ice cover in the arctic region and changes in strength and directions of ocean currents. This may result in major changes in the marine flora and fauna. Climate models simulate a higher temperature increase (in fact, double) in the arctic region compared to the global average (ACIA 2005). Furthermore, an increase in ocean temperature of 1 to 2 °C can influence fish stocks, as species will migrate northwards (ACIA 2005). More precipitation, run-off from the continent and melting ice from glaciers may decrease the salinity in the sea and have consequences for biological production (ACIA 2005).

2. CO_2 capture and storage

IPCC (2005) defines CO_2 capture and storage as a “process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere”. The captured CO_2 needs to be transported to a storage site where it will be stored away from the atmosphere for a very long time. This present OSPAR report covers solely storage in geological formations off-shore. Storage may also take place on land for which different safety and monitoring considerations will apply.

Capture of CO_2 is currently only practicable from large point-sources, typically power plants, large industrial plants, petroleum processing and certain industrial processes. Large-scale storage will therefore only be possible if there are a sufficient number of suitable CO_2 sources located near suitable storage sites (IPCC (2005) defines this to be 300 km). In western Europe, along with North America and parts of Asia, there are a large number of point sources meeting these requirements. Projections have shown that in 2050 20-40 % of global fossil fuel CO_2 emissions will be suitable for capture (IPCC 2005). If hydrogen is widely used as an energy carrier (for example, in road transport), the number of sources suitable for capture will increase as production of hydrogen fuel will take place in large point sources.

Experience with CCS

Large-scale injection of CO_2 started in 1972 in the Permian Basin in Texas, USA. The objective was to enhance the oil recovery (EOR) from exhausted oil fields by displacing more oil towards the production wells. CO_2 proved to be a very effective injection fluid for this purpose. When the oil prices increased in the mid 1970s many new projects were started. Today there are more than 70 ongoing CO_2 EOR projects and almost 40 million tonnes of CO_2 are being injected each year. These operations have provided a lot of experience in handling large quantities of CO_2 with respect to separating CO_2 from other gases, compression, transport, injection, corrosion control etc. A comprehensive infrastructure exists in form of a large CO_2 pipeline system supplying oil reservoirs with CO_2 from sources up 800 km from the oil fields. Most of the CO_2 comes from deep natural underground accumulations of $CO_{2,}$ while about 5% comes from industrial sources. In one of the more recent large-scale EOR projects, approximately 2 million tonnes of CO_2 per year are transported through a 320 km long pipeline from a coal-gasification plant in Dakota, USA, across the border to Saskatchewan, Canada, where the CO_2 is injected into the Weyburn oilfield to revive the oil production from the oilfield, which has been producing oil since 1955.

In more recent years, the interest in CO_2 injection has also resulted in projects where the CO_2 is injected into geological formation that are not bearing any oil (aquifers). In these projects, the incentive for injection is not to enhance oil recovery but simply to avoid emitting CO_2. The first project of this kind was started in 1996 at the Sleipner gas field in the North Sea, Norway. Approximately 1 million tonnes of CO_2 per year have since then been injected into a deep saline aquifer consisting of a 200 m thick sandstone layer at a depth of 1040 m. The extracted natural gas contains 9% CO_2 which is too much for delivery to the markets on the continent of Europe. The CO_2 is therefore removed from the extracted gas and injected. A similar injection project started 2004 at InSalah, Algeria, where the targeted injection rate is 1.1 million tonnes per year.

A number of other commercial or pilot storage projects have been implemented, or are under way, in Europe, including K12B (Netherlands), Ketzin (Germany), Snøhvit in the Barents Sea (Norway) and the Miller field in the North Sea (UK). In addition, there are several projects in other parts of the world. Some of these have the ultimate purpose of storing CO_2, while others are motivated by EOR. Using CO_2 for EOR has a double benefit and can make storage of CO_2 less costly (IPCC, 2005; Torvanger at al., 2005). The costs of capture typically are higher per tonne of CO_2 abated than the costs of transport and storage. The future cost-effectiveness depends on the prospects of reduced capture costs and the CO_2 emission-permit costs (or tax levels).

CCS in other international fora

IPCC has produced a special report on CO_2 capture and storage (IPCC 2005). This comprehensive report describes current knowledge of all aspects of capturing and storing CO_2, including costs, environmental impacts, risks and gaps in knowledge. The most policy-relevant questions are addressed in the Summary for Policy Makers (http://www.ipcc.ch/activity/ccsspm.pdf). One key conclusion is that clarification is needed about potential legal constraints on storage in the marine environment (ocean or sub-seabed geological storage). The subsidiary body of scientific and technological advice (SBSTA) under the United Nations Framework Convention on Climate Change (UNFCCC) had this report on its agenda in 2005. They welcomed the report and acknowledged CO_2 capture and storage as a mitigation option for stabilization of atmospheric greenhouse-gas concentrations. It encouraged Parties, the private sector and other potential developers to support the acceleration of research, development, deployment and diffusion of carbon dioxide capture and storage technologies. SBSTA will further address CO_2 capture and storage at its session in November 2006, based on a workshop arranged in spring 2006.

The IPCC is also producing guidelines for greenhouse gas inventories to be finalised in 2006. These are expected to be adopted by SBSTA at its session in spring 2006. These guidelines will be used for negotiation of new commitments for reducing emissions and enhancing sinks. The IPCC guidelines describe and recommend methods for estimation and verification of emissions and removals and quality assurance/quality control and reporting requirements. The 2006 Guidelines include a chapter on carbon dioxide capture and storage. This chapter will describe emission pathways and acceptable methods of estimating emissions from capture, transport, injection and storage. However, because of the state of knowledge, it will not suggest default leakage rates. It will also suggest a format for reporting capture, transport, injection and accumulated storage of CO_2 and associated emissions and will address other issues related to reporting (for example cross-border issues).

The 27th Consultative meeting of Contracting Parties to the London Convention October 2005 acknowledged that CO_2 sequestration in sub-seabed geological structures had a role to play, as part of a portfolio of measures to tackle the challenge of climate change and ocean acidification. Furthermore, the meeting decided that the London Convention is the appropriate global forum to address the implications of CCS for the marine environment, and should consider options for facilitating and/or regulating CO_2 sequestration in sub-seabed geological structures, including clarification (and, if appropriate, amendment) of the Protocol and the Convention.

The Carbon Sequestration Leadership Forum (CSLF) is currently working on two Discussion Papers one on “Identifying Gaps in CO_2 Monitoring and Verification of Storage”, and one on “Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity”.

3. The potential for storage of CO_2 in Europe

There is a significant potential for geological storage in structures in the OSPAR maritime area, including storage in EOR-projects. In two EU projects, the potential storage capacity for CO_2 in Europe has been mapped. These studies have shown that there is a significant storage capacity and that the potential is sufficient for injecting most of the EU’s CO_2 emissions from point-sources for perhaps hundreds of years. Most of this storage capacity is, however, located offshore, where most of the geological strata suitable for storage are located. Typically, the areas most suitable for safe and long-term storage are those where oil or gas has been trapped and saline formations (aquifers). In Europe, a large part of the storage capacity is located in the North Sea, as shown in the projects GETSCO and JOULE II. Because of the intensive exploration for oil and gas in this area, there is already a good knowledge of sub-seabed geology in the North Sea and also, for the same reasons, in the Norwegian Sea, the Barents Sea and the Aegean Sea. Since the oil- and gas-bearing structures have been storing buoyant fluid for millions of years, there are good chances of finding suitable similar structures for CO_2 storage, including depleted gas and oil reservoirs.

IPCC (2005) concludes that there is sufficient global storage capacity to contribute to stabilization of CO_2 concentrations. They estimate a technical potential of storing at least about 2,000 Gigatonnes of CO_2, the largest part in deep saline formations. This estimate is uncertain, and conservative, due to uncertainties on costs and lack of evaluation of the suitability of potential storage sites. The storage capacity matches quite well the suitable sources that are available.

4. Selection of geological structure for storage to avoid leakage

Relevant factors for the assessment of the suitability for CO_2 storage of geological structures in respect of both the protection of the marine environment and climate-change mitigation, include characterisation of the reservoir, the cap rock, geological stability, possible leakage-path routes and trapping mechanisms. Since the underground injection of CO_2 is a mitigation option against climate change, it must be performed under a specific regulatory framework if credit is to be earned for a country in meeting its emission-reduction commitments. Reporting methods specific for CCS is expected to be provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The general guidance in the existing IPCC guidelines can be applied to CCS. A few countries currently do so, in combination with their national methods for estimating emissions (IPCC 2005).

Oil and gas reservoirs

Oil and gas reservoirs can be used for CO_2 storage, both when the reservoir is depleted and when CO_2 is used for enhanced oil recovery (EOR). Since the capillary seal for these reservoirs has already proven its sealing integrity for buoyant fluids, the risk for leakage through these type of seals is unlikely, provided that the seal has not been damaged during exploitation of gas or oil.

One possible method by which pathways for leakage through the seal could be created is man-made wells that penetrate the seal. Since these wells are made of steel and cement that can possibly corrode or erode, special precautions need to be taken when these wells are abandoned. The wells should be plugged with materials that have a resistance to the reservoir fluids similar to that of the cap rock itself.

A second method by which pathways for leakage through the seal could be created is exposure of the cap rock to pressure differences that are so high that the seal will fracture. In normal operation of an oil or gas field, standard engineering practice aims to avoid this. If a reservoir is recognised as suitable for storage for $CO_{2,}$ the history of the field and its management should be fully documented.

Deep saline aquifers

For formations that have not been storing oil or gas, the verification of the integrity of the sealing rock is more challenging than for oil or gas fields. The basic method is to make a mathematical model of the geological structure and use this to predict the behaviour of injected CO_2 in mathematical simulations. The basic physical laws of how CO_2 migrates through porous media are well known, and can be modelled with a high level of accuracy if the transport properties of the rock are known. There exist several methods for exploring the reservoir to obtain the information necessary to build reliable models. These methods include the following:

Seismic surveys of the underground can reveal whether there are geological contrasts that can represent transitions between a more porous highly permeable reservoir and a tight sealing shale that can provide a capillary seal. The seismic results will give information on the extent and the topography that can both be used to determine the size of the reservoir and whether the seal will conduct the CO_2 into traps. Seismic surveys also determine location of faults and spill points.

Well logs can be obtained from wells that have been examined by various petrophysical methods to explore the properties of the rock the well is penetrating.

Core samples can be taken of the cap rock and the reservoir rock itself. These samples can be studied in a laboratory to obtain information on porosity, permeability, capillary pressure, multiphase flow properties and mechanical strength. X-ray diffraction can give information on the mineralogical composition, and microscopic methods can reveal additional structural and sedimentological information.

These methods can be used in combination to build the best geological model for predicting by simulation the behaviour of injected CO_2. This technology is similar to that used to predict the production of oil and gas from petroleum reservoirs. This technology has been developed rapidly during the last four decades along with the capacity of high-speed computers. The migration of CO_2 can also be located by repeated seismic surveys being carried out during the injection period. This can be used to verify the geological models and, if necessary, calibrate them to be consistent with the observed CO_2 behaviour (Figure ***1***).

5. Risk of leakage of CO_2

Storing CO_2 will imply a small, but nevertheless a certain, risk of leakage of CO_2 to the marine environment and the atmosphere. Based on current experiences, it is concluded that, in appropriately selected and managed geological reservoirs, the fraction retained is very likely[1] to exceed 99 % over 100 years and is likely[2] to exceed 99 % over 1000 years (IPCC 2005). Possible leakages, which may be gradual or abrupt, may occur through man-made structures such as well bores and wellheads, and geological pathways, such as undetected faults and factures. For wellselected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilized by various trapping mechanisms and could be retained for up to millions of years. Because of these mechanisms, storage could become more secure over longer timeframes. (IPCC 2005). This means that geological storage can be considered a safe way of mitigating climate change, provided that storage sites are appropriately selected, managed and monitored. The current knowledge on consequences of possible leakage is reviewed in section 7 of this report. Regulatory frameworks to ensure safe storage of CO_2 and monitoring are under development, and the most important are reviewed below. The discussions are limited to offshore storage since it is this which is relevant to the OSPAR Convention.

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[1] Probability between 90 and 99%.

[2] Probability between 66 and 90 %.

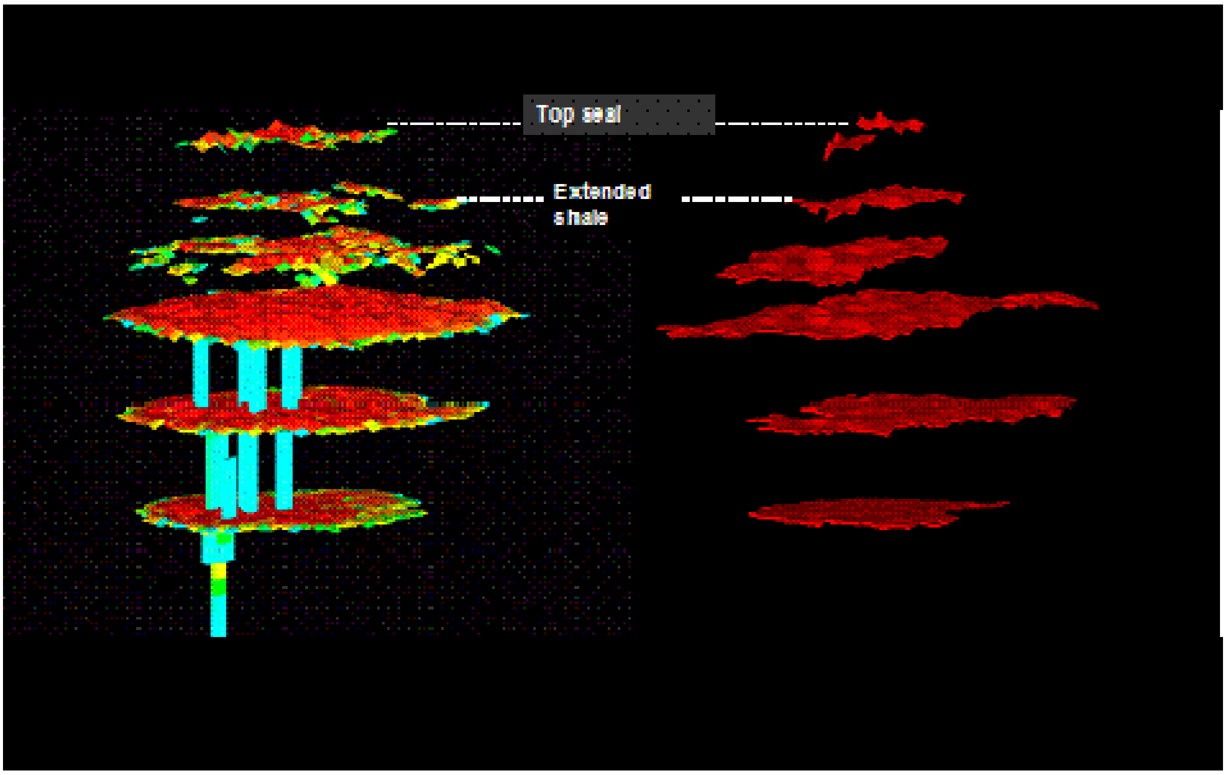

Figure 1. Simulated CO_2 bubbles at (left) and CO_2 bubbles observed by seismic after three years of injection (Sleipner CO_2 injection project)

According to another report **(**Bode and Jung 2005), it is still difficult to predict the seepage rates from long-term storage of very large volumes of CO_2 (OECD/IEA, 2004, p. 94 - 97). Storage site integrity depends on various factors (e. g. Jimenez et al. 2003). These include the geological characteristics of the reservoir, the history of human usage, and the quality of well and sealing packages and materials used including the long term stability of cement subjected to continuous exposure to CO_2. The retention time of CO_2 is therefore site and management specific. Furthermore, unforeseeable events, such as earthquakes, could lead to the rapid release of larger volumes of CO_2 from the reservoir. Criteria for site selection, management procedures and contingency planning could be seen as one means of guaranteeing the high environmental integrity of geological storage. These issues are further described in section 4 and 8.

6. Mechanisms retaining CO_2 underground

The driving force for CO_2 to migrate upwards in the reservoir is the buoyancy due to the density difference between CO_2 (300 kg/m^3) and brine (350 kg/m^3). This difference is about the same as the density difference between oil and brine. There are several mechanisms that are effective in preventing injected CO_2 from escaping from a reservoir into the atmosphere. The most important are:

The capillary seal (cap rock or sealing faults).

In general, an essential physical trapping mechanism is the presence of a cap rock acting as an upper seal to prevent CO_2 flow out of the reservoir. Such seals consist of fine shales with very small pores or geo-chemically deposited minerals in faults (geological upthrows). These minerals are water-wet and filled with brine. While the CO_2 is not wetting, the capillary entrance pressure defines the maxim excess pressure that the seal can hold. This is the most important trapping mechanism in an underground formation.

Pore trapping of CO_2

While CO_2 is being injected the CO_2, will form a continuous phase as long as the accumulations are growing. When the injection stops, there is a possibility that the CO_2 continues to migrate vertically or laterally. The continuous CO_2 phase will then be invaded by water from below. Because of the large surface tension between water and brine the continuous CO_2 phase will break at the pore throats and leave behind CO_2 bubbles of the same size as the pores. These will be permanently trapped and cannot give rise to further displacement of water despite the buoyancy force. How much of the CO_2 is trapped by this mechanism will depend heavily on the reservoir rock, heterogeneities and geometrical factors.

Dissolution of CO_2 in brine

The solubility of CO_2 in water is approximately 50 kg per m^3 under reservoir conditions. In porous media, dissolution is generally a slow mechanism that relies on molecular diffusion of the gas molecules in water. For the CO_2/water system, however, the dissolution can set up convective currents due to the CO_2-saturated brine being denser than brine without CO_2 (Lindeberg and Wessel-Berg 1996, Lindeberg and Bergmo 2002). Long-term predictions show that in some cases all CO_2 will eventually dissolve in the brine and (*e.g.* in the Sleipner case) no buoyant forces will remain on the CO_2 after a time period of a few thousand years (Figure 2). The dissolved CO_2 will then tend to move downwards in the reservoir.

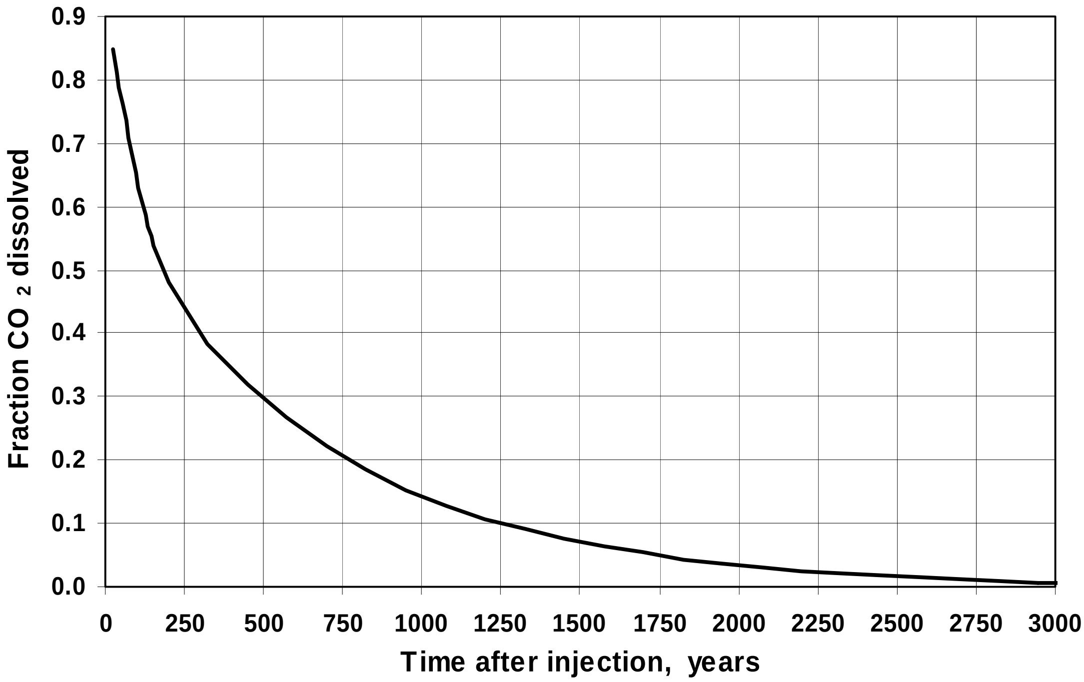

Figure 2. Dissolution of injected CO_2 at the Sleipner CO_2 injection project. The dissolution is strongly enhanced due to induced vertical convection. In this scenario 25 million tonnes CO_2 was originally injected.

Geochemical trapping of CO_2

When CO_2 dissolves in water it forms a weak acid that can react with some alkaline rock minerals. This will increase the storage capacity further. Some minerals may also form stable salts with carbonate that may permanently trap the CO_2 as minerals. These reactions are generally slow and are yet the least understood with respect to reaction rates.

7. Effects of CO_2 storage on the marine environment

As described in section 5, the risk for leakages from well selected and managed storage projects is expected to be low. Furthermore, geological storage of CO_2 sub-seabed[3] will only be an acceptable climate change mitigation option – related to the Framework Convention of Climate Change (UNFCCC) and the Kyoto Protocol (KP) - if the country concerned can verify that the stored CO_2 can be isolated from the atmosphere for the long term. Eventual leakages to the marine environment would be limited accordingly.

There is nevertheless a low-probability risk that stored CO_2 can leak from the storage site over time, or from the injection system during injection. This is considered the main risk to the environment. Additional low-probability risks are that pressure built-up caused by CO_2 injection could trigger small seismic events. If

3 In this context, "sub-seabed" refers to geological storage sites under the sea-bed, either in operating or depleted oil and gas reservoirs or saline aquifers.

leakage occurs at a storage site, remediation to stop the leakage could involve standard well-repair techniques or the interception and extraction of the CO_2 before it leaks. (IPCC 2005). Risk prevention and possible remediation actions will have to be addressed when an injection project is brought to an end - e.g. when installations are decommissioned. Environmental impacts of CO_2 leakage from geological storage could derive from the lowering of pH caused by the reaction of CO_2 when mixed with seawater. Removal of O_2 (and N_2) by bubble clouds of carbon dioxide could also occur. Impacts would be felt primarily by organisms near the leakage (e.g. zooplankton, bacteria and benthos) (Herzog et al. 1996 and Turley and Pörtner 2005). Leakage from offshore geological storage sites may also pose a hazard to benthic environments and organisms if the CO_2 moves from deep geological structures through benthic sediments to the ocean IPCC (2005).

The effects of CO_2 released into water bodies depend upon the magnitude and rate of release[4], the chemical buffer capacity of the water body, and transport and dispersion processes. pH changes in water are directly related to the partial pressure of CO_2 and the chemical buffer capacity of the water. High CO_2 levels in water may impair respiration in fish and cause acidosis and asphyxiation. The changes in ocean chemistry caused by CO_2 leakage may have profound effect on calcareous organisms such as corals, shellfish, and specific groups of phytoplankton. They may also disturb the physiology of non-calcifying animals. Effects may include reduced levels of growth and reproduction, as well as increased mortality rates. Furthermore, changes of pH due to CO_2 might have effects on metal speciation e.g. mobilising trace metals to a higher extent of bioavailability (Poremski, 2004).

NIVA (2005) and IPCC (2005) state that there are few or no actual studies of the environmental impacts from sub-seabed geological CO_2 storage projects. Some research is underway, for example by Monterey Bay Aquarium Research Institute and Norwegian Institute of Water Research (NIVA). Existing assessments of leaks from sub-sea operations or sub-seabed storage have mostly been for shallow waters, that is, less than 150m depth (NIVA 2005).

In general, IPCC (2005) concludes that the local health, safety and environmental risks of geological storage of CO_2 would be comparable to the risks of current activities such as natural gas storage, enhanced oil recovery (EOR) with injection mediums other than CO_2 and deep underground disposal of acid gas, provided that there is appropriate site selection, management and monitoring. This conclusion relates to both offshore and onshore geological storage. Some risks may be less severe for offshore projects compared with onshore projects - e.g. risk to humans and to ground water reservoirs.

Risk of leakage of CO_2 stored in sub-seabed geological structures has to be evaluated against the effects on the marine environment of the increased levels of CO_2 in the atmosphere. The upper layers of the oceans are well-saturated with CO_2 due to the air – sea fluxes of carbon dioxide (Poremski, 2004). The colder and deeper waters are usually undersaturated because of the long exchange times (*ibid*). The oceans are a massive natural reservoir of CO_2 and are also a natural sink of CO_2 produced through the burning of fossil fuels. The higher CO_2 consentrations in the surface waters of the oceans are changing the chemistry of the oceans. This has already resulted in a pH reduction – acidification – in the world's oceans of 0.1, from pH 8.2 to 8.1 over the last 200 years. Studies indicate, however that with a business-as-usual scenario of emissions, in the course of the next 100 years, pH might fall significantly, predictably to below 7.8, and possible to as low as 7.5. This is lower than that experienced in the last 10-20 million years. If the storage sites and injection procedures are selected carefully, the amounts potentially released into the ocean as a result of leakage can be expected to be smaller than the amounts expected to be absorbed into the oceans in the business-as-usual scenario (Turley and Pörtner 2005).

The potential ecological impact from the use of technologies for exploration and operation of sub-sea storages should be considered (e.g. when applying seismic techniques).

In a contribution to this report, WWF have expressed the following view: "Whilst companies and governments continue to seek and promote the exploration and development of further hydrocarbon resources, the reasons why we are faced with these risks continue to grow. If carbon dioxide is used as a tool for enhanced oil recovery from reservoirs, the negative feedback loops this approach brings mean that more oil will be produced, and thus potentially more reservoir storage required to attempt to eliminate the climate change problem." (WWF 2005) In this regard, it should also be noted that in many cases other types of enhanced oil recovery may be implied (e.g. injection of water or natural gas) if CO_2 is not used for this purpose. Furthermore this WWF statement is related to issues which are considered to be outside the scope of this report. It is therefore not commented upon further.

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[4] According to IPCC (2005), there are two types of leakages, i) abrupt leakages and ii) gradual leakage.

8. Monitoring of stored CO_2

Monitoring is a very important part of the overall risk management strategy for geological storage of CO_2. Various methods for monitoring stored CO_2 are available and should be used in a site-specific manner to detect and enable the remediation of leakage. The techniques are based on decades of experience in oil and gas development and production. Development of full-scale storage projects is therefore important for gaining experience and reducing the uncertainty connected with the measurements. New monitoring methods may also be developed in the future. All of the existing industrial scale projects and pilot projects have monitoring programmes using several types of techniques.

CO_2 storage as an accepted climate change mitigation option will require a system for estimating emissions or monitoring that the storage is safe. Monitoring will also be needed to verify that the CO_2 is properly injected and that the CO_2 injected remains separated from the atmosphere and, if leakages are detected, to determine the optimal remediation technology and to estimate emissions to be included in the greenhouse-gas inventories (IPCC 2005). The issue of long-term liability for CO_2 storage is addressed in the literature but is regarded as outside the scope of this report.

Monitoring of the following potential sources is relevant for OSPAR, as well as for performance in climate change mitigation:

a) ***injection into the reservoir through a well***. Adequate safety features are needed to reduce the risk of blow outs and leakages, including selection of suitable materials and maintenance. The wellhead should be monitored for leakage. Standard techniques for metering pressure, flow and composition of gas passing the well head are available and can be used to check that all injected gas is properly entering the reservoir. Monitoring can build on experience from oil and gas extraction processes,

b) ***EOR operations*** where CO_2 is injected to the reservoir, but a fraction of the amount injected will be associated with the produced oil,

c) ***the storage site***. Potential leakage points could include failure of the cap rock, faults and abandoned wells penetrating the reservoir.

As mentioned above, use of CO_2 capture and storage as an effective mitigation option requires storage for centuries to millennia (IPCC, 2005). Direct measurements of fluxes may not be possible for off-shore deep sea geological storage of CO_2. Monitoring has therefore to rely on indirect methods, e.g. monitoring amounts and movement of CO_2 in the reservoir. The main purpose of deep monitoring systems is to monitor amounts and movement of CO_2 within the storage reservoir and migration into its immediate surroundings. Deep monitoring systems can also give early warning of CO_2 migration to shallower depths in the overburden. Hence, deep monitoring would be an important part of a monitoring program. Such monitoring techniques can be run both from the surface (e.g. seismic surveys and gravity techniques) and in wells. Shallow monitoring systems aim to monitor CO_2 if it should migrate into the shallow overburden, into the soil or into the sea bed. High-quality baseline data improve the reliability and resolution of the monitoring and will be essential for detecting small rates of leakage. This is also important in order to define the appropriate combination of monitoring techniques for a specific storage site (IPCC 2005; DTI 2005) Techniques to monitor safe storage (deep subsurface only[5]) are briefly reviewed below.

There will be no one single monitoring strategy suitable for all sites because of differences in geological characteristics. The methods may also be, to some extent complementary. Furthermore, new or improved monitoring methods may be developed in the future. Site operators will need to demonstrate suitability of techniques for each case. Leakage routes can be identified by several techniques and by characterisation of the storage reservoir. The monitoring strategy can be developed to address these possible leakage routes. Experience expected in the next few years can be used to specify further suitability of monitoring options in a regulatory framework.

It is expected that some parameters, such as injection rate and injection well pressure, will be monitored routinely. So far, seismic techniques provide by far the most powerful subsurface imaging capability (DTI 2005). They utilize acoustic energy to detect changes in acoustic properties of the storage site to detect replacement of natural water with (less dense) CO_2. The technique can also be used to detect migration of CO_2 upwards and to quantify the total amount of CO_2 in the reservoir. There is a range of seismic techniques available. Conventional 3D seismic techniques can image CO_2 in the reservoir and detect migration

[5] Other techniques are suitable for shallow subsurface monitoring and onshore sites.

upwards. 4D seismic techniques (time-lapse mode) can also map changes in fluid distribution and pressure. The techniques need to be tested and assessed with regard to reliability, resolution and sensitivity in the context of geological storage. The storage site can also be monitored at surface or inside wells to detect gas escape mechanisms or gas plumes.

Gravimetric techniques can give much the same information as seismic, but at a coarser spatial resolution (IPCC 2005; DTI 2005). Electromagnetic techniques are recent developments, but have characteristics that can make them useful for monitoring sub-sea stored CO_2. Geochemical techniques involve analysis of the chemistry of fluids and gases, and can be used to compare measured concentrations with background levels. The seawater can be sampled for enhanced CO_2 concentrations, but this technique may not be practical for deep sea storage. Direct studies of ecosystems may potentially also be used to detect leakages indirectly. However, this would require better knowledge about the relationship between leakages and ecosystem impacts.

The determination of an optimal and cost-effective frequency of monitoring is an essential part of a monitoring strategy. Monitoring would need to be most comprehensive shortly after injection. The frequency can decrease as confidence increase in safe storage (DTI 2005). Monitoring is also crucial in research and pilot projects to gain more experience. Effective monitoring should build on reservoir simulations (models) showing the likely migration pathways of CO_2 over time. There are few estimates of monitoring costs. One study has estimated discounted costs at less than $ 0.1 per tonne of CO_2 (assuming monitoring for up to 80 years). This would mean that costs are not a barrier to monitoring (Benson et al. 2004; DTI 2005).

Greenhouse-gas inventories reported under UNFCCC are reviewed annually by an expert review team. The team consists of inventory experts from different countries around the world. The focus of the review is whether the requirements of the IPCC Guidelines are adequately followed by the Party under review. If the review team identifies serious problems with the inventory, this can have consequences for a Party's compliance with its commitments and/or its ability to participate in emission trading. It is not expected that members of a team reviewing the energy sector will always have detailed knowledge about CO_2 capture and storage. However, UNFCCC is training their reviewers and may provide additional training in this field. Nevertheless, pending decisions by UNFCCC and official bodies of regional emission trading schemes (e.g. European Union), there can be requirements for independent auditing in order to receive credits for this mitigation option.

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